

## BOSE-EINSTEIN CONDENSATE

# Bose-Einstein condensate

### Physics

A state of matter that occurs when a set of atoms is cooled almost to absolute zero in which a statistical description of the positions of the atoms implies that they physically overlap each other and in effect form a single atom

NOTE: The uncertainty principle of physics claims that if the velocity of an atom is sufficiently well defined, its position becomes proportionately ill defined. By cooling a set of atoms to only a little bit above absolute zero, their velocity can be determined fairly accurately, to the point where their theoretical positions overlap each other. At this point, the atoms can all be treated as if they exist in the same quantum state and are part of a single large atom.

Take a rarefied gas—atoms darting around in a container—and cool it so that the motion becomes slower and slower. Each atom's wavelength will widen until finally, as the temperature nears absolute zero, they all overlap, forming an exotic substance called a *Bose-Einstein condensate*. George Johnson, *The New York Times*, 16 Oct. 2001

### Etymology

after Satyendra Nath *Bose* †1974 Indian physicist and  
Albert *Einstein* †1955 American physicist born in Germany

# Bose-Einstein condensate

state of matter

**Bose-Einstein condensate (BEC)**, a state of matter in which separate [atoms](#) or [subatomic particles](#), cooled to near [absolute zero](#) (0 K,  $-273.15\text{ }^{\circ}\text{C}$ , or  $-459.67\text{ }^{\circ}\text{F}$ ; K = kelvin), coalesce into a single [quantum mechanical](#) entity—that is, one that can be described by a [wave function](#)—on a near-macroscopic scale. This form of matter was predicted in 1924 by [Albert Einstein](#) on the basis of the [quantum](#) formulations of the Indian physicist [Satyendra Nath Bose](#).

Although it had been predicted for decades, the first atomic BEC was made only in 1995, when [Eric Cornell](#) and [Carl Wieman](#) of JILA, a research institution jointly operated by the [National Institute of Standards and Technology](#) (NIST) and the [University of Colorado](#) at Boulder, cooled a [gas](#) of [rubidium](#) atoms to  $1.7 \times 10^{-7}$  K above absolute zero. Along with [Wolfgang Ketterle](#) of the [Massachusetts Institute of Technology](#) (MIT), who created a BEC with [sodium](#) atoms, these researchers received the 2001 [Nobel Prize](#) for Physics. Research on BECs has expanded the understanding of quantum [physics](#) and has led to the discovery of new physical effects.

BEC theory traces back to 1924, when Bose considered how groups of [photons](#) behave. Photons belong to one of the two great classes of elementary or submicroscopic particles defined by whether their quantum [spin](#) is a [nonnegative integer](#) (0, 1, 2, ...) or an odd half [integer](#) ( $1/2$ ,  $3/2$ , ...). The former type, called [bosons](#), includes photons, whose spin is 1. The latter type, called [fermions](#), includes [electrons](#), whose spin is  $1/2$ .

As Bose noted, the two classes behave differently (see [Bose-Einstein](#) and [Fermi-Dirac statistics](#)). According to the [Pauli exclusion principle](#), fermions tend to [avoid](#) each other, for which reason each electron in a group occupies a separate quantum state (indicated by different [quantum numbers](#), such as the electron's energy). In contrast, an unlimited number of bosons can have the same energy state and share a single quantum state.

Einstein soon extended Bose's work to show that at extremely low temperatures "bosonic atoms" with even spins would coalesce into a shared quantum state at the lowest available energy. The requisite methods to produce temperatures low enough to test Einstein's prediction did not become attainable, however, until the 1990s. One of the breakthroughs depended on the novel technique of laser cooling and trapping, in which the [radiation pressure](#) of a [laser beam](#) cools and localizes atoms by slowing them down. (For this work, French physicist [Claude Cohen-Tannoudji](#) and American physicists [Steven Chu](#) and [William D. Phillips](#) shared the 1997 Nobel Prize for Physics.) The second breakthrough depended on improvements in magnetic confinement in order to hold the atoms in place without a material container. Using these techniques, Cornell and Wieman succeeded in merging about 2,000 individual atoms into a "superatom," a condensate large enough to observe with a microscope, that displayed distinct quantum properties. As Wieman described the achievement, "We brought it to an almost human

scale. We can poke it and prod it and look at this stuff in a way no one has been able to before.”

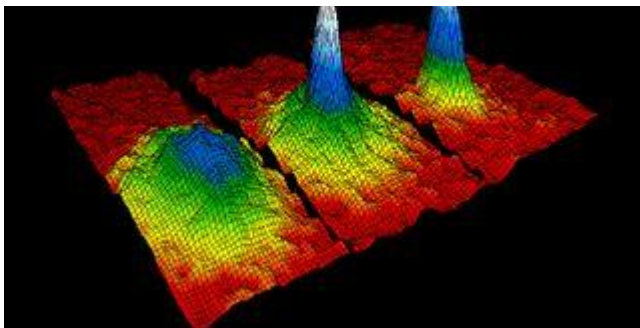
BECs are related to two remarkable low-temperature phenomena: [superfluidity](#), in which each of the [helium isotopes](#)  $^3\text{He}$  and  $^4\text{He}$  forms a [liquid](#) that flows with zero [friction](#); and [superconductivity](#), in which electrons move through a material with zero [electrical resistance](#).  $^4\text{He}$  atoms are bosons, and although  $^3\text{He}$  atoms and electrons are fermions, they can also undergo Bose condensation if they pair up with opposite spins to form bosonlike states with zero net spin. In 2003 Deborah Jin and her colleagues at JILA used paired fermions to create the first atomic fermionic condensate.

BEC research has yielded new atomic and optical physics, such as the [atom](#) laser Ketterle demonstrated in 1996. A conventional light laser emits a beam of [coherent](#) photons; they are all exactly in [phase](#) and can be focused to an extremely small, bright spot. Similarly, an atom laser produces a coherent beam of atoms that can be focused at high intensity. Potential applications include more-accurate [atomic clocks](#) and [enhanced](#) techniques to make electronic chips, or [integrated circuits](#).

The most intriguing property of BECs is that they can slow down light. In 1998 [Lene Hau](#) of [Harvard University](#) and her colleagues slowed light traveling through a BEC from its speed in vacuum of  $3 \times 10^8$  metres per second to a mere 17 metres per second, or about 38 miles per hour. Since then, Hau and others have completely halted and stored a light pulse within a BEC, later releasing the light unchanged or sending it to a second BEC. These manipulations hold promise for new types of light-based [telecommunications](#), [optical storage](#) of data, and [quantum computing](#), though the low-temperature requirements of BECs offer practical difficulties.

## Bose-Einstein condensate: The fifth state of matter

A Bose-Einstein condensate is a strange form of matter in which extremely cold atoms demonstrate collective behavior and act like a single "super-atom."



In the 1920s, Satyendra Nath Bose and Albert Einstein first conceived of a strange form of matter in which individual atoms clump together and behave like a single super atom. But scientists Eric A. Cornell and Carl E. Wieman only demonstrated it seven decades later, in ultracold rubidium atoms. Here, a series of images show, from left to right, increasing density as those rubidium atoms begin to form a BEC. (Image credit: NIST/JILA/CU-Boulder - NIST Image)

The Bose-Einstein condensate (BEC) is one of the five primary [states of matter](#). In it, atoms reach such low energies that the rules of [quantum mechanics](#) dictate that they stop acting as individual atoms and behave like a single "super atom."

A Bose-Einstein condensate forms only when materials are cooled to within a hair of [absolute zero](#). At that temperature the atoms are hardly moving relative to each other; they have almost no free energy to do so. The atoms then begin to clump together, and enter the same energy states. They become identical, from a physical point of view, and the whole group starts behaving as though it were a single atom.

[Gases](#), [liquids](#), [solids](#) and [plasmas](#) have been studied for decades, if not centuries, but Bose-Einstein condensates weren't created in the laboratory until the 1990s. To make a Bose-Einstein condensate, you start with a cloud of diffuse gas. Many experiments start with atoms of [rubidium](#). Then you cool it with lasers, using the beams to take energy away from the atoms. After that, to cool them further, scientists use evaporative cooling.

"With a [Bose-Einstein condensate], you start from a disordered state, where kinetic energy is greater than potential energy," Xuedong Hu, a professor of physics at the University at Buffalo, told Live Science. "You cool it down, but it doesn't form a lattice like a solid."

Instead, the atoms fall into the same quantum states, and can't be distinguished from one another. At that point the atoms start obeying what are called Bose-Einstein statistics, which are usually applied to particles you can't tell apart, such as photons, or light packets.

## Theory and discovery

Bose-Einstein condensates were first predicted theoretically in the 1920s by Satyendra Nath Bose (1894-1974), an Indian physicist who also discovered the subatomic particle named for him, the boson. Bose was working on statistical problems in quantum mechanics, and sent his ideas, which pertained to photons, to [Albert Einstein](#) according to the [American Physical Society](#).

Einstein thought them important enough to get them published. As importantly, Einstein saw that Bose's mathematics — later known as Bose-Einstein statistics — could be applied to atoms as well as light. The two published a series of papers laying out the details of this strange form of matter in 1924, according to the APS.

What the two found was that ordinarily, atoms have to have certain energies — in fact one of the fundamentals of quantum mechanics is that the energy of an atom or other subatomic particle can't be arbitrary. This is why electrons, for example, have discrete "orbitals" that they have to occupy, and why they give off photons of specific wavelengths when they drop from one orbital, or energy level, to another. But cool the atoms to within billionths of a degree of absolute zero and some atoms begin to fall into the same energy level, becoming indistinguishable. That's why the atoms in a Bose-Einstein condensate

behave like "super atoms." When one tries to measure where they are, instead of seeing discrete atoms one sees more of a fuzzy ball.

Other states of matter all follow the Pauli Exclusion Principle, named for physicist Wolfgang Pauli. Pauli (1900-1958) was an Austrian-born Swiss and American theoretical physicist and one of the pioneers of quantum physics. His principle dictates that fermions — particles such as quarks and leptons that make up matter — can't be in identical quantum states. This is why when two electrons are in the same orbital, their spins must be opposite so they add up to zero. That, in turn, is one reason why chemistry works the way it does and why atoms cannot occupy the same space at the same time. Bose-Einstein condensates break that rule.

Though Bose and Einstein's work predicted such states of matter should exist, it wasn't until 1995 that a team led by Eric A. Cornell and Carl E. Wieman, both of the Joint Institute for Lab Astrophysics (JILA) in Boulder, Colorado, [managed to make one of rubidium atoms](#), and MIT's Wolfgang Ketterle and colleagues, [made one of sodium atoms](#), that we had experimental confirmation of their existence. The trio shared the 2001 [Nobel Prize](#) in Physics for this work.

In July 2018, an experiment aboard the [International Space Station](#) cooled a cloud of rubidium atoms to ten-millionth of a degree above absolute zero, [producing a Bose-Einstein condensate in space](#). They repeated the demonstration of a [BEC on the ISS](#) in 2020. The experiment also now holds the record for the coldest object we know of in space, though it isn't yet the coldest thing humanity has ever created.

And in 2023, scientists at the University of Chicago created the first BEC which demonstrated a strange phenomenon, called [quantum superchemistry](#). In that strange quantum phenomenon, individual atoms in a BEC chemically react all at once. In the experiment, scientists convincingly showed that thousands of [cesium atoms bonded all at once to form cesium molecules](#), then near-instantaneously converted back to cesium atoms.

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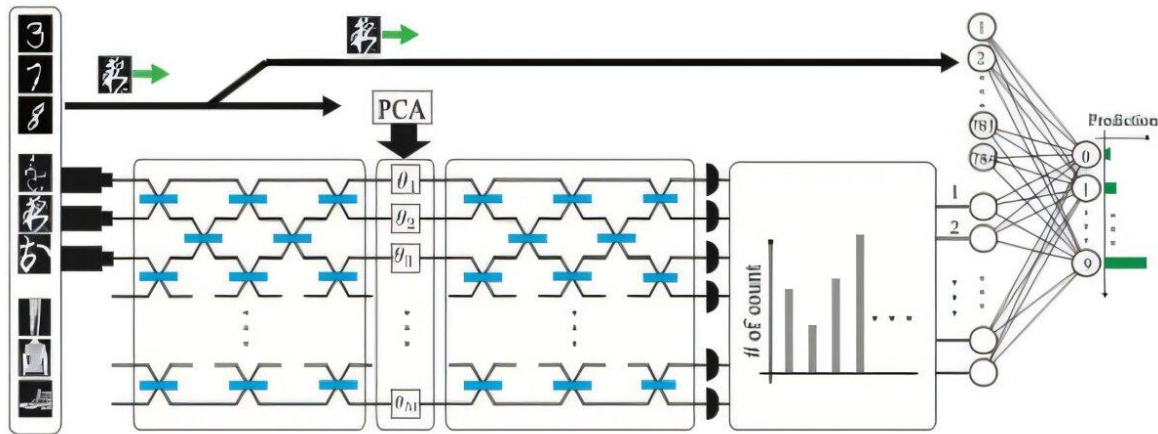
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[The GIST](#)

# Boson sampling finds first practical applications in quantum AI

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In their simulated system, image data is first simplified using a process called principal component analysis (PCA), which reduces the amount of information while preserving key features. Credit: Sakurai et al., 2025

For over a decade, researchers have considered boson sampling—a quantum computing protocol involving light particles—as a key milestone toward demonstrating the advantages of quantum methods over classical computing. But while previous experiments showed that boson sampling is hard to simulate with classical computers, practical uses have remained out of reach.

Now, in *Optica Quantum*, researchers from the Okinawa Institute of Science and Technology (OIST) [present the first practical application of boson sampling for image recognition](#), a vital task across many fields, from forensic science to medical diagnostics. Their approach uses just three photons and a linear optical network, marking a significant step towards low energy quantum AI systems.

## Harnessing quantum complexity

Bosons—particles like photons that follow Bose-Einstein statistics—exhibit complex interference effects when passed through certain optical circuits. In boson [sampling](#), researchers inject single photons into one such circuit, then measure the output probability distribution after they interfere.

To understand how such sampling works, think of marbles on a pegboard. When the marbles are dropped, if you sample the probability distribution of where the marbles land, it forms a bell curve. However, the results are completely different when running this same experiment using single photons.

They display wave-like properties, so can interfere with one another, and interact with their environment very differently from large objects. This means that they display very complex probability distributions, which are hard for classical computing methods to predict.

## From quantum reservoir to image recognition

In this paper, the researchers developed a new quantum AI method for image recognition based on boson sampling. In their simulated experiment, they began by generating a complex photonic quantum state, onto which simplified image data was encoded.

The researchers used gray scale images from three different data sets as input. Since each pixel is in gray scale, the information is easy to represent numerically, and could be compressed using [principal component analysis](#) (PCA) to retain key features.

This simplified data was encoded into the [quantum system](#) by adjusting the properties of single photons. The photons then passed through a quantum reservoir—a complex optical network—where interference created rich, high-dimensional patterns.

Detectors recorded photon positions, and repeated sampling built a boson sampling probability distribution. This quantum output was combined with the original image data and processed by a simple linear classifier.

This hybrid approach preserved information and outperformed all comparably sized machine learning methods that the researchers tested, providing highly accurate image recognition across all data sets.

"Although the system may sound complex, it's actually much simpler to use than most quantum machine learning models," explained Dr. Akitada Sakurai, first author of this study, and member of the Quantum Information Science and Technology Unit.

"Only the final step—a straightforward linear classifier—needs to be trained. In contrast, traditional quantum machine learning models typically require optimization across multiple quantum layers."

Professor William J Munro, co-author and head of the Quantum Engineering and Design Unit, added, "What's particularly striking is that this method works across a variety of image datasets without any need to alter the quantum reservoir. That's quite different from most conventional approaches, which often must be tailored to each specific type of data."

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# Unlocking new frontiers in image recognition

Whether it's analyzing handwriting from a [crime scene](#), or identifying tumors in MRI scans, [image recognition](#) plays a vital role in many real-world applications. The promising results of this study found that this quantum approach identified images with higher accuracy than similarly sized machine learning methods, opening new avenues in quantum AI.

"This system isn't universal—it can't solve every computational problem we give it," noted Professor Kae Nemoto, head of the Quantum Information Science and Technology Unit, Center Director of the OIST Center for Quantum Technologies, and co-author of this study.

"But it is a significant step forward in quantum machine learning, and we're excited to explore its potential with more complex images in the future."

**More information:** Akitada Sakurai et al, Quantum optical reservoir computing powered by boson sampling, *Optica Quantum* (2025). DOI: [10.1364/OPTICAQ.541432](https://doi.org/10.1364/OPTICAQ.541432)  
Provided by [Okinawa Institute of Science and Technology](#)

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